GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No.: E-18-614 (R6015-0A0) GTRC/~~GIT~~ DATE 8 / 26/ 85

Project Director: E. E. Underwood School/~~Lab~~ Materials Eng.

Sponsor: National Science Foundation

Type Agreement: Grant DMR-8504167

Award Period: From 8/15/85 To ~~7/31/87~~* 1/31/89 (Performance) ~~4/30/87~~ 4/30/89 (Reports)

Sponsor Amount: This Change / Total to Date

Estimated: $ ______ $ 182,700

Funded: $ ______ $ 75,000

Cost Sharing Amount: $ 3,860 Cost Sharing No: E-18-312

Title: Quantitative Analysis of Fracture Surfaces Using Stereological Methods

ADMINISTRATIVE DATA

OCA Contact John Schonk x4820

1) Sponsor Technical Contact:
Craig S. Hartley
~~Manfred Wuttig~~
National Science Foundation
MPS/DMR
Washington, DC 20550
202/357-9789

2) Sponsor Admin/Contractual Matters:
Shirley P. Greene
~~Myra E. Galvin~~
National Science Foundation
DGC/MPS
Washington, DC 20550
202/357-9671

Defense Priority Rating: ~~N/A~~ U Military Security Classification: ~~N/A~~ N
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

COMMENTS:

*Includes 6 month unfunded flexibility period.

No funds may be expended after 1/31/87.

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NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 04/30/91

Project No. E-18-614 Center No. R6015-0A0

Project Director GOKHALE A M School/Lab MAT ENGR

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. DMR-8504167 Contract Entity GTRC

Prime Contract No.

Title QUANTITATIVE ANALYSIS OF FRACTURE SURFACES USING STEREOLOGICAL METHODS

Effective Completion Date 910131 (Performance) 910430 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	N	
Final Report of Inventions and/or Subcontracts	Y	910426
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

CommentsBILLING VIA NSF LOC

Subproject Under Main Project No.

Continues Project No.

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PROGRESS REPORT FOR PERIOD 15 Aug 1985 - 14 Aug 1986

Our objectives during the period are to apply the general fractographic analyses developed previously to the treatment of (1) specific features in the fracture surface, (2) the damage associated with crack initiation and growth, and (3) microstructural changes that accompany the fracture process. These results will be used to formulate more realistic models and relationships for fatigue crack propagation and the fracture process.

In our current research we are studying the fracture characteristics of 4340 steels, isothermally tempered at 650 C for times up to 100 hours. Microstructural and fractographic factors are being evaluated as a function of tempering times. Quantitative dimple attributes have been calculated for three types of fracture surfaces (planar, random and partially-oriented). Errors of over 100 percent are possible using the flat SEM fractograph directly without corrections. These, and other results are being presented at the TMS-AIME Annual Meeting in New Orleans on March 4, 1986.[1]

Fatigue crack proagation studies of underaged and overaged Al-4%Cu alloys have been undertaken in the near threshhold and Paris regimes. Statistical hypothesis testing criteria based on fracture profile and bulk microstructural parameters were developed. Closure and crack deflections are interpreted in terms of fracture profile parameters. These results will also be presented in New Orleans.[2]

In order to broaden the base of materials investigated, some preliminary studies are being planned on the damage and fracture behavior of a metal matrix composite (MMC) consisting of an Al-Li alloy matrix reinforced with continuous Al_2O_3 fibers.

As mentioned in our previous Progress Report [3] our in-depth studies of fracture profiles indicated results contrary to the postulates of Mandelbrot[4]. Accordingly, we have proposed new analytical procedures, new fractal equations, and defined new fractal dimensions -- for both fracture profiles <u>and</u> fracture surfaces. These findings were submitted to Materials Science and Engineering and have been promptly accepted for publication in March or April 1986.[5]

Other activity currently underway during this Report Period includes a detailed assessment of fracture profiles and the parametric equations that relate the surface roughness to the profile roughness.[6] In addition, two major chapters are being written for the latest ASM Handbook Series in the volume on Fractography, on the subjects of "Quantitative Fractography"[7] and "Fractals in Fractography".[8] A further development, which is based on the general principles formulated for nonplanar surfaces, is an assessment of porous structures to be presented at the Gordon Conference on Foams, at Plymouth, NH from Aug 4 - 8, 1986.

References:

(1) E. E. Underwood and K. Banerji, "Recent Advancements in Quantitative Fractography", presented in session on "Stochastic Approaches to Fracture I", March 4, 1986. TMS-AIME Annual Meeting, New Orleans. (Abstract only)

(2) K. Banerji and E. E. Underwood, "Quantitative Analysis of Fracture Surface Morphology during FCP in High-Purity Al-4%Cu Binary Alloys", presented in session on "Fracture Toughness", ibid. (Abstract only)

(3) To Dr. Manfred Wuttig, DMR, NSF, dated Oct 24, 1985.

(4) B. Mandelbrot, The Fractal Geometry of Nature, W. H. Freeman and Co., San Francisco (1982), Ch. 6.

(5) E. E. Underwood and K. Banerji, "Fractals in Fractography", accepted by Materials Science and Engineering, (1986).

(6) E. E. Underwood, "Analysis of Fracture Roughness", Unpublished Ga Tech Report (1986).

(7) E. E. Underwood and K. Banerji, "Quantitative Fractography", for Vol. 9, Fractography in ASM Handbook Series, 9th Edition, (1986).

(8) E. E. Underwood, "Fractals in Fractography", ibid.

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Georgia Institute of Technology
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Atlanta, Georgia 30332-0100
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February 24, 1986

Dr. Manfred Wuttig
Metallurgy Program
Division of Materials Research
National Science Foundation
1800 G. Street, N.W.
Washington, D. C. 20550

Subject: Continuation documentation for period 15 Aug 1986 - 14 Aug 1987 for DMR 8504167

Dear Dr. Wuttig:

Enclosed are the budget and other information requested by telephone on Feb 18, 1986 for continuation of my NSF Grant DMR 8504167. The report follows the format outlined in your letters to me dated Aug 9, 1985 and Sept 13, 1985.

Originally, you may recall, I had submitted budgets for the entire 30 month period (totalling $181,867.). However, a revised budget was requested for the 12 month period Aug 15, 1985 - 14 Aug 1986. (See letter from Lynn Boyd, Contracting Officer at Georgia Tech, dated 17 July 1985, using an O.H. rate of 55.3%, and a letter from me on 24 Oct 1985, using an O.H. rate of 63.5 %.)

I trust the report enclosed herein contains the information you desire. Please let me know if I can be of any further help.

Sincerely yours

Ervin E. Underwood
Principal Investigator

Encls: 3 copies

PROGRESS REPORT FOR PERIOD 15 Aug 1985 - 14 Aug 1986

Our objectives during the period are to apply the general fractographic analyses developed previously to the treatment of (1) specific features in the fracture surface, (2) the damage associated with crack initiation and growth, and (3) microstructural changes that accompany the fracture process. These results will be used to formulate more realistic models and relationships for fatigue crack propagation and the fracture process.

In our current research we are studying the fracture characteristics of 4340 steels, isothermally tempered at 650 C for times up to 100 hours. Microstructural and fractographic factors are being evaluated as a function of tempering times. Quantitative dimple attributes have been calculated for three types of fracture surfaces (planar, random and partially-oriented). Errors of over 100 percent are possible using the flat SEM fractograph directly without corrections. These, and other results are being presented at the TMS-AIME Annual Meeting in New Orleans on March 4, 1986.[1]

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(1) E. E. Underwood and K. Banerji, "Recent Advancements in Quantitative Fractography", presented in session on "Stochastic Approaches to Fracture I", March 4, 1986. TMS-AIME Annual Meeting, New Orleans. (Abstract only)

(2) K. Banerji and E. E. Underwood, "Quantitative Analysis of Fracture Surface Morphology during FCP in High-Purity Al-4%Cu Binary Alloys", presented in session on "Fracture Toughness", ibid. (Abstract only)

(3) To Dr. Manfred Wuttig, DMR, NSF, dated Oct 24, 1985.

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(6) E. E. Underwood, "Analysis of Fracture Roughness", Unpublished Ga Tech Report (1986).

(7) E. E. Underwood and K. Banerji, "Quantitative Fractography", for Vol. 9, Fractography in ASM Handbook Series, 9th Edition, (1986).

(8) E. E. Underwood, "Fractals in Fractography", ibid.

I. Progress Report (1 October 1985 to 3 August 1986)

Our objective -- to develop an assumption-free, generally valid, statistically accurate procedure for determining the true magnitudes of features in the fracture surface -- is well along toward its realization. We have derived relationships based on geometric probabilities between quantities in the fracture surface and profiles from sections through the surfaces. Results calculated by means of these equations compare well with the known quantities of our Computer Simulated Fracture Surface. Moreover, all published experimental data between the roughness parameters for surface (R_S) and profile (R_L) fit our parametric equation between R_S and R_L better than other published equations. Based on this new ability to calculate true fracture surface areas (from R_S), we have proposed a fractal equation for irregular surfaces (not available heretofore) that conforms to actual rough, complex fracture surfaces. This new analysis was published in Materials Science and Engineering as an Invited Review.

A complete stereological and fractographic analysis procedure has been developed using an image analysis system interfaced with the GA Tech mainframe Cyber computer for calculations, printing and graphics. An efficient experimental package for determining surface areas, angular distributions, and lengths requires only standard metallographic facilities and a modestly-priced image analysis system. These procedures have been reviewed vis-a-vis the current options of quantitative fractography along with practical applications in the forthcoming ASM Vol. 12 on "Fractography and Atlas of Fractographs."

Experimentally, we have used a commercial ferrous alloy (4340) and a high-purity binary alloy (Al-4%Cu) to develop techniques and verify our analytical relationships. An outstanding finding was the extreme sensitivity of the numerical parameters for revealing subtle effects. For example, in a range of tempered specimens, the well-known 500°C embrittlement of 4340 steels was clearly revealed by roughness parameters, even though mechanical tests, SEM fractographs, profile characteristics, and metallography showed no apparent unusual appearance for the 500°C specimen. The changing fracture behavior of Al-4%Cu alloys as a result of aging treatment was clearly revealed by the angular distribution of normals along the corresponding profiles. These results were interpreted in terms of barriers of increasing strength, and increasing crack path deflection. Based on our relationships between fracture roughness parameters and measurements from the SEM fractograph, we are able to show errors of over 100 percent in the conventionally calculated values. The fatigue and FCP study of underaged and overaged Al-4%Cu alloys has brought forth several new and worthwhile findings. These are discussed thoroughly in the attached copy of K. Banerji's Ph.D. thesis.

A list of pertinent technical presentations and publications that acknowledge NSF support is appended separately.

I. Progress Report (15 August 1986 to 14 August 1987)

Our objective -- to develop an assumption-free, generally valid, statistically accurate procedure for determining the true magnitudes of features in the fracture surface -- is well along toward its realization. We have derived relationships based on geometric probabilities between quantities in the fracture surface and profiles from sections through the surfaces. Results calculated by means of these equations compare well with the known quantities of our Computer Simulated Fracture Surface. Moreover, all published experimental data between the roughness parameters for surface (R_S) and profile (R_L) fit our parametric equation between R_S and R_L better than other published equations. Based on this new ability to calculate true fracture surface areas (from R_S), we have proposed a fractal equation for irregular surfaces (not available heretofore) that conforms to actual rough, complex fracture surfaces. This new analysis was published in Materials Science and Engineering as an Invited Review.

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A set of pertinent technical presentations and publications that acknowledge NSF support has been sent to your attention previously.

PROGRESS REPORT

15 August 1987 to 31 July 1988

Our objective has been to develop an assumption-free, generally valid, statistical procedure for estimating the true magnitudes of features in the fracture surface. Relationships based on geometrical probabilities have been developed between quantities in the fracture surface and in profiles from sections through the surfaces. Calculated results compare well with the known quantities of our Computer Simulated Fracture Surface. Moreover, we have derived a general parametric relationship that gives the surface area of any complex, irregular, re-entrant surface in terms of roughness parameters. All known experimental data conform to our parametric equation better than any of the other published equations. In fact, we have been able to show that only our equation, out of some 12 others, falls within the theoretical upper and lower bounds to such relationships. Based on this new ability to calculate true fracture surface areas we have derived a fractal equation for irregular surfaces that complements our modified fractal equation for profiles. This new analysis was published in Materials Science and Engineering as an Invited Review. The more engineering aspects of our quantitative fractography and fractal work have been incorporated in two articles in the new ASM Handbook, Vol. 12, on Fractography.

The main thrust of our experimental work during this report period has centered on anisotropic materials, as epitomized by fiber-reinforced metal matrix composites. Specimens of unidirectional, continuous fibers of Al_2O_3 in a matrix of Al-2.5%Li have fiber orientations of 0, 30, 60 and 90-degrees with regard to the load axis. Because of the anisotropy, two-surface analyses are employed for the metallographic surfaces, the fracture profile studies, and the measurements of mechanical properties. The stereological measurements of fiber orientation, volume fraction, size and spacing are analyzed vis-a-vis the fracture path. Expressions have been derived that relate profile roughness to surface roughness as a function of anisotropy.

Considerable attention is placed on the problem of fiber clustering. We desire a parameter that expresses the degree of clustering quantitatively; for example, one that varies numerically from 0 to 1 as the fiber configurations change from uniform through random to clustered. Transverse section planes are cut perpendicular to the fiber axes. Using standard image analysis equipment, the fiber centers are simply touched with the electronic pencil on a digitizing tablet, giving the coordinates of each fiber. Computer programs then provide histograms of the first, second, third, etc. nearest neighbor spacings. Another approach under investigation involves the radial density of fibers averaged over all fibers. Broad peaks appear close to distances of 2r, 3r, etc., reminiscent of the radial atomic density curves of loosely-packed liquids as a function of distance, as obtained by small angle x-ray scattering.

PUBLICATIONS ACKNOWLEDGING NSF SUPPORT

(1) "Quantitative Fractography," with K. Banerji. In vol. 12, Fractography and Atlas of Fractographs, ASM Handbook Series, 9th Ed. (1987) 193-210.

(2) "Fractal Analysis of Fracture Surfaces," with K. Banerji. ibid., p. 211-215.

(3) "Stereological Analysis of Fracture Roughness Parameters," 25th Memorial Volume of the Int. Soc. for Stereology, ed. by R.E. Miles. Published by Acta Stereologica, Ljubljana, Yugoslavia, (1987) 169-178.

(4) "The Analysis of Nonplanar Surfaces by Sterological and Other Methods," Plenary Lecture, Session on Nonplanar Surfaces. Proc. 7th Int. Congr. for Stereology, Caen, France, ed. by M. Kalisnik, Ljubljana, Yugoslavia, (1987). Accepted for publication.

Presentations and Publications on Composites:

(5) "Quantitative Metallographic and Fractographic Analyses of MMC MIcrostructures," W.J. Drury, K. Banerji and E.E. Underwood. Proceedings Advanced Materials Conference, Denver, CO (1987).

(6) "Stereological Characterization of Fiber-Reinforced Metal Matrix Composites," W.J. Drury and E.E. Underwood, Proc. 7th Int. Congr. for Stereology, Caen, France, ed. by M. Kalisnik, Ljubljana, Yugoslavia, (1987). Accepted for publication.

ACTIVITY RELATING TO NSF GRANT

During this report period, from the above list, there have been four publications, four presentations, and two papers accepted for publication. In addition, the following presentations were made:

(1) "Fractals in Fractography," presented by E.E. Underwood at the TMS/AIME Annual Meeting, in session on "Fractal Applications in Materials Science," Denver, CO (1987).

(2) "Recent Advances in Quantitative Fractography," presented by E.E. Underwood, at ASM Materials Science Seminar, Cincinnati, OH, October, 1987.

FUTURE ACTIVITY

We are organizing a session on "Advances in Quantitative Fractography," 7th Int. Conf. on Fracture, Houston, TX, March, 1989.

RESEARCH PLAN FOR THE NEXT YEAR

The study of fracture characteristics of anisotropic materials will be continued, with specific reference to metal-matrix composites. Three types of prototype materials with different fiber configurations will be studied:

(a) Continuous and unidirectional fibers

(b) Discontinuous and unidirectional fibers

(c) Discontinuous and randomly-oriented fibers.

The metallographic, fractographic and mechanical properties of samples of these three types of configurations will be characterized quantitatvely. Mechanical properties will derive from tensile, fatigue and/or creep tests.

The analyses of the results will involve such topics as fiber orientation effects, interface strengths, relative crack preference for interface vs. matrix, fracture modes, damage initiation and progression, etc. The theory of anisotropic elasticity will be invoked, as well as the stress configurations developed at the fiber interfaces and ends in the three configurations listed above.

The overall objective is to develop a predictive capability that will give the magnitude of properties as a function of direction for a material with known fiber orientation and load direction.

THESES ACKNOWLEDGING NSF SUPPORT

Two Master's theses are in the process of being written. One is by William J. Drury and the other is by Karen S. Ringel, both being on the subject of metal matrix composites.

RESIDUAL RUNDS

It is anticipated that there will be no residual funds at the end of this grant period.

CURRENT AND PENDING SUPPORT
S. D. ANTOLOVICH

Source of	Project Title	Award Amount	Period Covered by Award	% of Effort Acad.	Sum	Location Where Research Is Performed
Current						
NASA	1	$268,391	12/15/83-12/31/88	16	16	Ga. Tech
AFOSR	2	$119,770	5/1/87-4/30/90	12	12	Ga. Tech
Cummins Engine	3	$75,440	9/25/86-9/30/88	10	10	Ga. Tech
McDonnell Douglas	4	$58,800	6/1/87-6/30/88	oversight responsibility		Ga. Tech
McDonnell Douglas	5	$50,799	10/1/87-9/30/88	12	12	Ga. Tech
Pending						
NSF-MRG (PI/PD, A. Saxena)	6	$1,779,015	7/88-6/913	25	25	Ga. Tech

Project Titles

1. "Micromechanistic Deformation Response of Anisotropic Alloys Under Repeated Loading"
2. "Cyclic Deformation, Damage and Effects of Environment on the Ni_3Al Ordered Alloy at Elevated Temperatures"
3. "Fatigue Behavior of Piston Alloys"
4. "Elevated Temperature Testing"
5. "High Temperature Fatigue Behavior of Materials Used in Advanced Air-Frame Structures"
6. "Structure, Deformation and Fracture Mode Characterization of Anisotropic Materials

PROGRESS REPORT

August 1988 - February 1989

The basic objective of this project work has been to develop unambiguous and assumption free, and yet practically feasible and flexible techniques for quantitative characterization of the geometry of fracture surfaces and the microstructural features present on such surfaces. Such rigorous quantification can yield important input concerning deformation and fracture mechanisms responsible for the generation of fracture surface, and the role of microstructural features in the fracture processes. We are very pleased with our progress during the recent past; significant results have emerged both in the theoretical and experimental components of the research work. The main results are presented below.

I. THEORETICAL DEVELOPMENTS:

The Quantitative fractography must be based on solid theoretical grounds, and should not involve geometry or feature specific assumptions. The important quantitative descriptors of fracture surface geometry are as follows.

(i) Fracture surface roughness

(ii) Fracture surface anisotropy quantified by the orientation distribution function (ODF).

(iii) Quantitative measure of overlaps and,

(iv) Fractal characteristics.

Important theoretical results were derived concerning these descriptors.

(i) **Fracture Surface Roughness**: A new parametric equation has been derived to calculate the surface roughness R_S of symmetric fracture surfaces from the measurement of vertical section profile roughness parameter R_L. The equation is derived via infinite power series expansion of the orientation distribution function; an excellent agreement with experimental data on variety of different materials has been demonstrated. These results are scheduled for publication in Acta Stereologica in the very near future (paper no. 1 in the list of publications acknowledging NSF support). A simple parametric equation has been also derived for the estimation of surface roughness R_S of a nonsymmetric fracture surface (fracture surfaces of composites fall in this category) from measurements of profile roughness parameters on two specific perpendicular sections. This result formed the basis for quantitative fractography of Al_2O_3 fiber reinforced composite material having Al-Li matrix; one student has recently completed the M.S. thesis project on this topic.

(ii) **Anisotropy of Fracture Surface**: Each surface element on the fracture surface has an orientation specified by its normal vector. The frequency distribution function of these orientations basically quantifies the 'skeleton' of fracture surface, which is independent of its metric characteristics. A geometrically general stereological relationship has been derived for the estimation of Orientation Distribution Function (ODF) of surface elements on symmetric fracture surface from the measurement of orientation distribution function of line elements on fracture profile (PODF).

The two distributions are related through an Abel type integral equation. This development completely generalizes the results of Scriven and Williams for equiaxed, monosize planar facets; the present result does not involve any such assumptions. We have also developed stereological technique for estimation of ODF of nonsymmetric fracture surfaces of composite materials, from the measurements of PODF on two or more fracture profiles generated by sectioning planes of different known orientations. These results should be very useful for the fracture surfaces of composite materials. In general, the ODF of fracture surfaces should contain information concerning stress condition responsible for fracture, and hence it should be useful for failure analysis.

(iii) **Quantitative Measure of Overlaps**: Fracture surfaces often contain overlapped regions, and fraction of fracture surface area having overlaps is an important descriptor which gives additional information on the nature of fracture surface. The extent of overlaps may depend on operative fracture mechanisms, and hence this parameter may be useful for verification of some fracture models. Two slightly different techniques have been developed for quantifying the fraction of overlapped fracture profile; the appropriate parametric equations are then utilized to calculate the fraction of fracture surface area having overlaps.

(iv) **Fractal Characteristics**: The fracture profiles exhibit a peculiar type of 'fractal' behavior; the total profile length increases with the decrease in 'ruler' length, till a saturation value is reached. These results were obtained by Banerji and Underwood a few years back for the fracture profiles of metallic materials. We have now observed similar Pattern in the fracture profiles of composite materials. The selection of optimum measurement resolution and ruler length are thus important factors for quantitative fractographic measurements. This problem has been systematically analyzed and the results are reported in a paper (no. 2 in the list of publications acknowledging NSF support) scheduled for publication in Microstructural Science in the near future. It is shown that if the fracture profile consists of coarse facets then a relatively coarse ruler length can yield reliable estimates of the profile characteristics.

II. EXPERIMENTAL WORK

We have done extensive experimental work on quantitative fractography of Al_2O_3 fiber reinforced Al-Li alloy matrix composite material. The fracture surfaces were generated by uniaxial tensile stress as well as by cyclic fatigue loading. These experiments were repeated for different relative orientations of fibers with respect to stress axis, and also for samples having different volume fractions of Al_2O_3 fibers. The results are reported in two M.S. thesis completed recently. The stereological measurements were carried out on metallographic sectioning planes through bulk, and quantitative fractographic measurements were performed on fracture profiles and SEM fractographs. This experimental program involving rigorous quantitative characterization has yielded interesting and useful results. The measurements of spatial distribution of fiber centers via digital image analysis techniques and comparison of these measurements with Monte Carlo computer simulations have resulted in estimation of quantitative measure of clustering tendency of fibers in this composite material. Such objective quantitative information should be useful for processing of fiber reinforced composites. We have also developed methodology to assess the role of processing defects such as voids, oxide inclusions, oversize fibers, split fibers etc. in the fracture of these composites. Although all the defects present in the bulk material are seen on the fracture surface, comparison of parameters such as area fraction, number density, and average size (calculated after appropriate accounting of surface roughness) of different types of defects with their corresponding values on a sectioning plane through bulk material, yields information on importance of different types of processing defects in fracture. For example, in the case of Al_2O_3 fiber/Al-Li matrix composites, area fraction of voids and inclusions on fracture surface have comparable values (which may be misconstrued to mean that both these defects are equally deleterious), however, comparison with corresponding values in a sectioning plane through bulk material clearly shows that voids are more deleterious!

Another important conclusion which has emerged from this study is that, not only the largest defects but a significant spectrum of defect sizes play important role in the failure process. It would not have been possible to arrive at these conclusions from qualitative observations. These ruminations demonstrate that quantitative fractography can be now applied to study engineering problems concerning materials processing.

A paper based on some of these results has been recently submitted to Met. Trans. for publication. An overview containing our theoretical and experimental results has been submitted for ASTM special technical publication very recently. Further, Dr. Underwood has been invited to organize a session on "Advances in Quantitative Fractography" in 7th International Conference on Fracture, scheduled in March 1989; he is also invited to present a paper on récent developments in this field.

PUBLICATIONS ACKNOWLEDGING NSF SUPPORT

1. 'A New Parametric Roughness Equation for Quantitative Fractography" by A.M. Gokhale and E.E. Underwood, Acta Stereologica, in press.

2. "Criteria For Selecting The Optimum Resolution For Quantitative Analysis of Fracture Surfaces" by A.M. Gokhale and K. Banerji, Microstructural Science, in press.

3. "Application of Quantitative Fractography and Computed Tomography to Fracture Processes in Materials" by S.D. Antolovich, A.M. Gokhale, and C. Bathias, ASTM Special Technical Publication, communicated.

4. "Involvement of Processing Defects in Failure of FP/Al-Li" by W.J. Drury, Met. Trans., communicated.

5. "Modern Methods for the Quantitative Analysis of Nonplanar Surfaces" by E.E. Underwood, J. Microscopy (special issue for Stereology)", 1989, communicated.

6. "Recent Advances in Quantitative Fractography" by E.E. Underwood, ASM Materials Science Seminar, Cincinnati, OH, accepted for publication.

   Paper no. 3 in the list of publications was presented in ASTM symposium on Fractography held in Atlanta in November 1988.

THESES ACKNOWLEDGING NSF SUPPORT

W.J. Drury completed his master's thesis in November 1988.
K.S. Ringel completed her M.S. thesis in July 1988.

OMB Number 345-0058

NATIONAL SCIENCE FOUNDATION
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WASHINGTON, DC 20550

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PI/PD Name and Address

Arun Manedeo Gokhale
School of Materials Engineering
Georgia Tech Research Corp
Georgia Institute of Technology
Atlanta GA 30332

NATIONAL SCIENCE FOUNDATION
FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org. Bruce A. MacDonald - DMR

2. Program Name METALS, CERAMICS, & ELECTRONIC MATERIALS

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4. Institution and Address
Georgia Tech Research Corp
Administration Building
Atlanta GA 30332

5. Award Number 8504167

6. Project Title
Quantitative Analysis of Fracture Surfaces using Stereological Methods

This Packet Contains
NSF Form 98A
And 1 Return Envelope

PART IV — FINAL PROJECT REPORT — SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in response to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the information.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	1		0	0	1	1	0	0	0	0
B. Total, Permanent Residents	1		0	0	1	0	0	0	0	0
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native										
Asian	1				1					
Black, Not of Hispanic Origin										
Hispanic										
Pacific Islander										
White, Not of Hispanic Origin										
C. Total, Other Non-U.S. Citizens										
Specify Country 1.										
2.										
3.										
D. Total, All participants (A + B + C)	2	0	0	0	2	1	0	0	0	0
Disabled[3]										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1]Category includes, for example, college and precollege teachers, conference and workshop participants.

[2]Use the category that best describes the ethnic/racial status for all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3]A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America, and who maintain cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia and the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the original peoples of Hawaii; the U.S. Pacific Territories of Guam, American Samoa, or the Northern Marianas; the U.S. Trust Territory of Palau; the islands of Micronesia or Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.

THIS PART WILL BE PHYSICALLY SEPARATED FROM THE FINAL PROJECT REPORT AND USED AS A COMPUTER SOURCE DOCUMENT. DO NOT DUPLICATE IT ON THE REVERSE OF ANY OTHER PART OF THE FINAL REPORT.

A.M. Gokhale
DMR - 8504167

PART - II

SUMMARY OF COMPLETED PROJECT

The basic objective of this research was to develop unambiguous, unbiased, assumption - free, and practically feasible as well as flexible stereological techniques for quantitative characterization of the geometric attributes of fracture surfaces and microstructural features in three dimensional space. The quantification of structural and fractographic properties is expected to provide important input concerning the deformation and fracture processes that are responsible for material fracture and failure; these studies are crucial for the improvement of existing materials, and for the development of new materials. The basic components of the research work were analytical theoretical work, digital image analysis, computer simulation and calculations, and experimental measurements on the fracture surfaces of a low alloy steel, aluminum - copper alloy, and a metal matrix composite. As the characterization techniques are absolutely general, they are equally applicable to biological, pathological, botanical, and geological structures. Some of our results are being used by biologists for the characterization of blood vessels, microtubules, neurons, etc. (see enclosed copies of SQM news letters). A very general method has been developed for the measurement of roughness of a fracture surface of any arbitrary geometry. A stereological method has been also developed for quantification of anisotropy of symmetric fracture surfaces. We have utilized digital image analysis for characterization of fracture profiles. These methods were utilized to study the role of processing defects in the fracture of a metal

matrix composite, detection of temper embrittlement in steel via fractal dimension measurement, and effect of microstructure on the fracture processes in an aluminum alloy, etc.

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PART - III

TECHNICAL INFORMATION

The end point of deformation and fracture processes is the generation of fracture surface. It may be said that the geometric attributes of fracture surface and the associated microstructural features contain quantitative information concerning the processes that lead to fracture. In order to develop such correlations among fractographic attributes, fracture behavior and properties, and material microstructure, it is essential to utilize the structure characterization techniques that are assumption free and unbiased, so that the observed correlations are real, <u>and</u> the real correlations <u>are</u> observed. The main objective of this research was to develop the general, assumption free, and unbiased stereological techniques for quantitative characterization of fracture surfaces and microstructures in three dimensional space from the observations and measurements that can be performed on the associated lower dimensional manifolds. The basic components of this research were analytical theoretical work involving the applications of stochaistic geometry, fractal geometry, differential geometry, and integral geometry, digital image analysis for quantitative measurements, computer simulations, and experimental measurements on the fracture profiles and microstructures. A very significant progress has been made during the course of this project work. This research has provided very important input in the development of new science of quantitative fractography. Our results are reported in more than twenty publications in prestigious journals and conference proceedings (the publication list is enclosed). The following is a very brief summary of this progress.

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(1) The experimental techniques for the vertical section profilometry and digital image analysis of fracture profiles were established for the quantification of fracture surface Profiles (publication no. 9,10,11,15)

(2) A computer code was developed to calculate profile roughness, fractal dimension, and profile line element angular orientation distribution function from the digitized profile co-ordinate data obtained by digital image analysis. (Publication no.11, 12)

(3) The above experimental methods were successfully applied to the fracture profiles of low alloy steel, aluminum-copper alloy, and metal matrix composite material (publication no. 5,19,11,13,15,16)

(4) Resolution dependent fracture profile roughness parameter was studied in detail to establish the reverse sigmoidal behavior which describes the ruler length or resolution dependence of profile roughness. A computer program was developed to calculate the fractal dimension of fracture profile and the saturation roughness from the experimental data (publication no. 6,12,18,19,21)

(5) The techniques established in (1) to (4) were utilized to study variation of the fractal dimension of fracture profile of test fracture surfaces with the tempering temperature in a low alloy steel. It was shown that the temper embrittlement leads to a significant decrease in the profile fractal dimension (publication no. 11, 12)

(6) The profile roughness data was successfully utilized to analyze fatigue crack growth behavior in a low alloy steel.

(7) The utility of quantitative fractographic techniques was demonstrated via experimental

work on the fracture profiles from the fracture surfaces of Al-Cu alloy (publication no. 10)

(8) A computer program was developed to calculate anisotropy of symmetric fracture surfaces from the profile line element angular orientation distribution function (publication no. 10)

(9) A computer program was developed to calculate spatial distribution of fibers in a metal matrix composite from digitized certroid co-ordinate data, and it was utilized to quantify the spatial distribution of continuous unidirectional Al_2O_3 fibers in Al-Li alloy matrix.

(10) Quantitative SEM fractography was utilized to analyze the role of processing defects in the fracture of metal matrix composite material (publication no. 5, 8).

(11) A general, assumption - free, and unbiased stereological relationship has been derived to estimate roughness (and hence the surface area) of any arbitrary fracture surface from the measurements performed on the corresponding vertical section fracture profiles; the result is a fundamental equation of quantitative fractography (publication no. 3)

(12) The efficiency and precision of the above general method for surface roughness measurement was studied in detail via extensive computer simulations. It was shown that just three vertical sections which are mutually at an angle of 120°, contain sufficient structural information for estimation of surface roughness of anisotropic fracture surface (publication no. 4)

(13) A design based efficient stereological method was developed to estimate the length densities of the lineal microstructural feature from the measurements performed on their projected images; this result is utilized by biologists for the estimation of the length density of blood vessels, microtubles, neurons, etc. (see pub. no 2, and enclosed copies of SQM news letters).

(14) A set of design based test line shapes have been theoretically calculated for efficient quantification of anisotropy of lines in two dimensional plane; the intersection counts with these test lines directly yield the Fourier coefficients that quantify the anisotropy.

(15) The stereological techniques were utilized to characterize the anisotropic fracture surfaces of metal matrix composite materials (publication 4,5, 14).

(16) The stereological methods were utilized to quantitatively analyze the creep fracture processes (publication no. 1).

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LIST OF PUBLICATIONS ACKNOWLEDGING NSF SUPPORT

1. A.M. Gokhale, "Utility of Stereological Counting Measurements in the Study of Creep Cavitation Kinetics", Proceedings of MiCon-90, ASTM Special Tech. Pub. No. 1049, George F. VanderVoort ed., pp. 332-339, 1991.

2. A.M. Gokhale, "Unbiased Estimation of Curve Length in 3D Using Vertical Slices", Journal of Microscopy, vol. 159, pt. 2, pp. 133-141, 1990.

3. A.M. Gokhale and E.E. Underwood, "A General Method for Measurement of Fracture Surface Roughness - I; Theoretical Aspects", Metall. Trans., vol, 21A, pp. 1193-1199, 1990.

4. A.M. Gokhale and W.J. Drury, "A General Method for Measurement of Fracture Surface Roughness - II; Practical considerations." Metall. Trans., vol. 21A, pp. 1201-1207, 1990.

5. S.D. Antolovich, A.M. Gokhale and C. Bathias, "Application of Quantitative Fractography and Computed Tomography to Fracture Processes in Materials", ASTM Special Tech. Pub. No. 1085, B.M. Strauss and S.K. Patatunda, eds., pp. 3-25, 1990.

6. A.M. Gokhale and K. Banerji, "Criteria for Selecting Optimum Resolution For Quantitative Analysis of Fracture Surfaces", Microstructural Science, vol. 17, pp. 67-79, 1989.

7. A.M. Gokhale and E.E. Underwood, "A New Parametric Roughness Equation For Quantitative Fractography", Acta Stereologica, vol. 8, pp. 43-52, 1989.

8. W.J. Drury, "Involvement of Processing Defects in Failure of FP.Al-Li", Metall. Trans., vol. 20A, pp. 2175-2178, 1989.

9. E.E. Underwood, "Estimating Feature Characteristics by Quantitative Fractography", Jnl. of Metals, vol. 38, No. 4 (1986) 30-33.

10. K. Banerji and E.E. Underwood, "On Estimating the Fracture Surface Area of Al-4% Cu Alloys", Microstructural Science, vol. 13, ed. by S.A. Shield, et al., 17th Annual Technical Meetings of the Inter. Metallographic Soc., Philadelphia, (1987) 537-551.

11. E.E. Underwood and K. Banerji, "Quantitative Fractography", in Fractography, vol. 12, Metals Handbook, 9th Edition, ASM International, (1987) 193-210.

12. E.E. Underwood and K. Banerji, "Fractal Analysis of Fracture Surfaces", ibid., 211-215.

13. E.E. Underwood, "Stereological Analysis of Fracture Roughness Parameters", 25th Memorial Volume of the Inter. Soc. for Stereology, ed. by R.E. Miles, Publ. by Acta Stereologica, Ljubljana, Yugoslavia, (1987) 169-178.

14. W.J. Drury and E.E. Underwood, "Quantitative Fractographic Analyses of Oriented Fracture Surfaces", Proc. 7th Inter. Congr. for Stereology, Pt. II, ed. by J.-L. Chermant, Vol. 6, Suppl. III, (1987) 549-554.

15. E.E. Underwood, "The Analysis of Nonplanar Surfaces Using Stereological and Other Methods", ibid., 855-876.

16. W.J. Drury, K. Banerji and E.E. Underwood, "Quantitative Metallographic and Fractographic Analyses of MMC Microstructures", Proc. Advanced Mats. Conf., ed. by J.G. Morse, Publ. by The Met. Soc., Warrendale, PA (1987) 279-287.

17. E.E. Underwood, "The Current Status of Modern Quantitative Fractography", Advances in Fracture Research, vol. 5, ed. by K. Salama, et al., Seventh Int. Conf. on Fracture, Pergamon Press, (1989) 3391-3409.

18. E.E. Underwood, "Recent Advances in Quantitative Fractography", Fracture Mechanics: Microstructure and Mechanisms, ed. by S.V. Nair, et al., ASM International, (1989) 87-109.

19. E.E. Underwood, "The New Quantitative Fractography for Analyzing Metallic Surfaces", Jnl. of Metals, vol. 42, No. 10 (1990) 10-15.

20. E.E. Underwood, "Evaluation of Overlaps in Fracture Surfaces", MiCon 90: Advances in Video Technology for Microstructural Control, ASTM STP 1094, ed. by G.F. Vander Voort, American Society for Testing and Materials, Philadelphia (1990) 340-353.

21. E.E. Underwood, "Treatment of Reversed Sigmoidal Curves for Fractal Analysis", ibid., 354-364.

22. E.E. Underwood, "Directed Measurements and Heterogeneous Structures in Quantitative Fractography", Proc. STERMAT '90, Third Conf. on "Stereology in Materials Science", Szczyrk, Poland Publ. by Polish Soc. for Stereology (1990) 100-115.